

The Coupled Boundary Layers and Air-Sea Transfer Experiment in Low to Moderate Winds (CBLAST-LOW):

Flux Profile Relationships Across the Coupled Boundary Layers

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Upper Ocean Dynamics and Horizontal Variability in Low Winds

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Award Number: N00014-01-1-0029

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LONG-TERM GOALS

The long-range goal of the proposed research is to understand air-sea interaction and coupled atmospheric and oceanic boundary layer dynamics at low wind speeds where the dynamic processes are driven and/or strongly modulated by thermal forcing. The low wind regime will extend from the extreme situation where wind stress is negligible and thermal forcing dominates up to wind speeds where wave breaking and Langmuir circulations are also expected to play a role in the exchange processes. Therefore, the CBLAST-LOW investigators seek to make observations over a wide range

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2003		2. REPORT TYPE		3. DATES COVERED 00-00-2003 to 00-00-2003	
4. TITLE AND SUBTITLE The Coupled Boundary Layers and Air-Sea Transfer Experiment in Low to Moderate Winds (CBLAST-LOW):Flux Profile Relationships Across the Coupled Boundary Layers				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Woods Hole Oceanographic Institution, MS #12,,98 Water Street,,Woods Hole,,MA,02543				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 14	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

of environmental conditions with the intent of improving our understanding of upper ocean and lower atmosphere dynamics and of the physical processes that determine both the vertical and horizontal structure of the marine boundary layers.

OBJECTIVES

The objectives of the *Flux Profile Relationships Across the Coupled Boundary Layers* component (hereafter the tower component) are to obtain direct measurements of vertical fluxes (transfer) of momentum, heat and mass across the coupled boundary layers (CBLs); to map the 3-D structure of the CBLs over a range of spatial and temporal scales, to identify the processes that drive the flux and CBL structure; to develop and evaluate parameterizations of the flux-producing processes; and to test the mean and variance budgets for momentum, heat, mass, and kinetic energy. The objectives of the *Upper Ocean Dynamics and Horizontal Variability in Low Winds* component (hereafter the array component) are to observe and understand in low wind conditions how and why the vertical structure and properties of the surface boundary layer of the ocean evolve in time, and how and why this evolution varies at horizontal lags of 10s of meters to 10s of kilometers on time scales of minutes to months. To do so we seek to observe and identify the processes that spatially modulate the vertical structure of the upper ocean (including the depth, salinity, temperature, and velocity of the mixed layer), the processes at work at the base of the mixed layer (such as entrainment), and (3) the air-sea exchanges (fluxes of heat, freshwater, and momentum) that couple the boundary layers on horizontal scales of tens of meters up to 100 km.

Little work has been done to explore air-sea interaction and upper ocean dynamics in very light winds, and few observations are available that describe the mesoscale and smaller scale horizontal variability of the upper ocean and lower atmosphere in such conditions. Therefore, observational components of this program will investigate the temporal and spatial evolution of the CBLs over vertical scales of from centimeters to 100's of m, horizontal scales of from 10 m to 10's of km, and time scales of minutes to months. Mesoscale models, large eddy simulations (LES), and direct numerical simulations (DNS) will provide nowcasts, forecasts, and simulations over similar scales. The numerical results will provide a context for interpreting our measurements, while our measurements will provide a means to initialize and evaluate the estimates of turbulent fluxes and dissipation rates calculated by these models.

APPROACH

To achieve some of these objectives, the array component deployed a 3-D mesoscale array to simultaneously observe the horizontal and vertical structure of the oceanic surface boundary layer south of the tower as shown in Fig. 1. This mooring component also conducted intensive ship-based surveys during the intensive operating period (IOP). The ship-based surveys were coordinated with the two aircraft-based efforts that investigated spatial variability of the atmospheric boundary layer and sea surface temperature field. The combined data sets will be used in conjunction with the modeling studies to seek answers to unresolved questions about how the vertical as well as the horizontal structure of the coupled boundary layers evolve.

The tower component has deployed an Air-Sea Interaction Tower (ASIT) spanning the water column and the lower 22-m of the atmosphere at a water depth of 15-m at the Martha's Vineyard Coastal Observatory (MVCO) and shown in Figs. 1 and 2. The 37-m tower has been instrumented with velocity, temperature, conductivity, pressure, humidity, solar radiation, turbidity, precipitation and

wave sensors. The tower is connected directly to shore using a fiber-optic-conductor cable, which provides Gbyte bandwidth and kWatts of power to the researchers. The velocity and temperature arrays span horizontal and vertical scales of O (1-10) m to resolve vertical structure and to permit separation and quantification of processes associated with shear- and buoyancy-generated turbulence, surface waves, and Langmuir-like coherent structures.

CBLAST 2003 Offshore Array

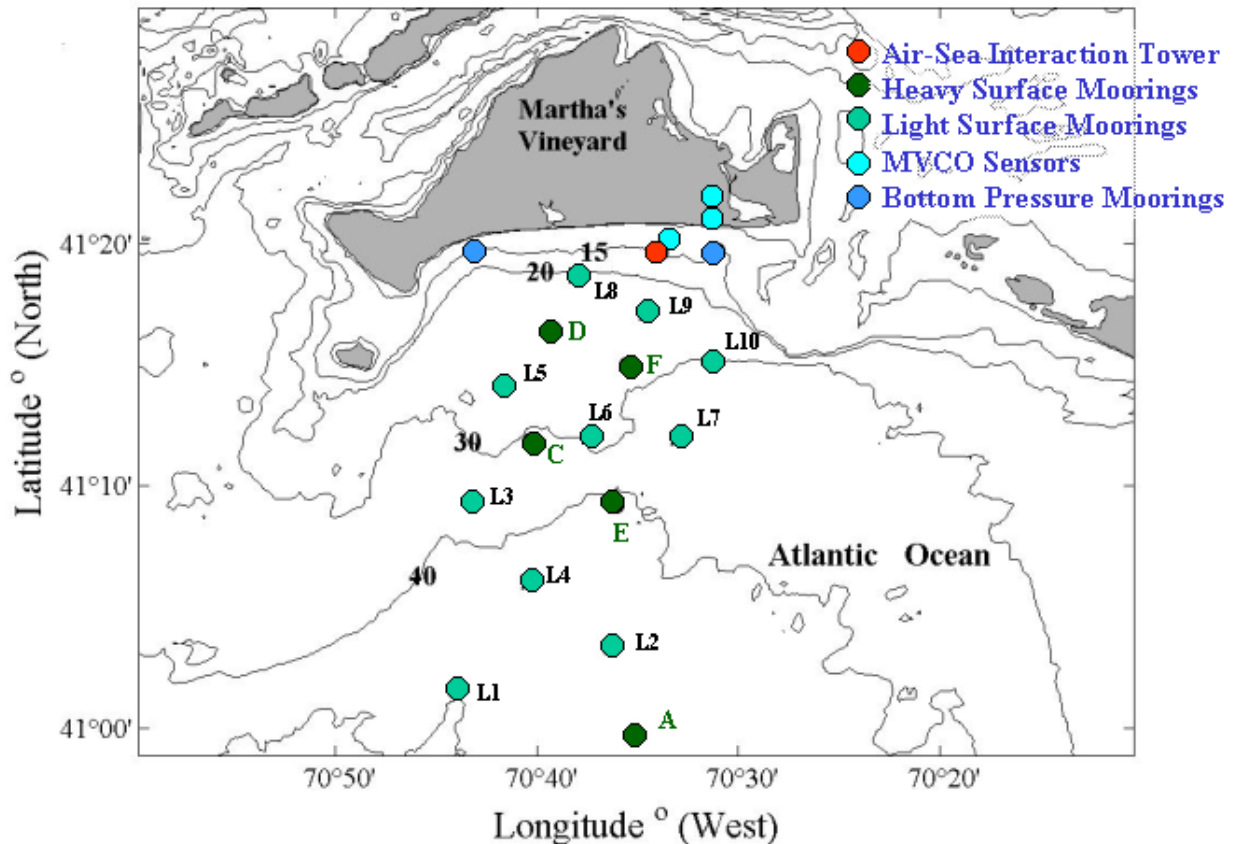


Figure 1. A diagram of the CBLAST region showing some of the assets that were deployed during the main experiment IOP in the summer 2003.

The IOP of the main experiment was recently completed in August of 2003 (with some components continuing into the fall). The field work during the IOP involved substantial collaborations with Tim Stanton (NPS) deploying complementary sensors at the ASIT; Larry Mahrt and Dean Vickers (OSU), Jielun Sun (NCAR), Djamal Khelif (UCI), and Haf Jonsson (CIRPAS) obtaining atmospheric measurements of turbulent fluxes, vertical profiles and horizontal variability from the LongEZ aircraft in 2001 and the CIRPAS Pelican aircraft in 2003; and Andy Jessup (UW) and Chris Zappa (WHOI) obtaining IR remote-sensing measurements. In addition, we have had substantial collaborations with regional-scale modeling groups at Rutgers University and NRL-Monterey, as well as LES investigations by Eric Skillingstad at OSU and Peter Sullivan at NCAR. The regional-scale models are providing a context for interpreting our measurements, and our measurements will provide a means of testing estimates of turbulent fluxes and dissipation rates calculated by these models. The tower measurements of horizontal and vertical variability spanned a range of scales similar to those resolved

by LES simulations and will permit a quantitative evaluation of LES model calculations. The proposed study will produce a unique set of simultaneous measurements of turbulent fluxes and dissipation rates on both sides of the air-sea interface, as well as critical evaluations and improvements of turbulence parameterizations used in atmospheric and oceanic models. The mooring and ship survey measurements spanned a range of scales required to investigate processes on the mesoscale and, in combination with the aircraft measurements, will permit a quantitative evaluation of the coupled mesoscale model results.

WORK COMPLETED

The ASIT, completed in the late summer of 2002, was outfitted with an electronics node and directly connected to the Martha's Vineyard Coastal Observatory (MVCO) in the fall of 2002 to provide data transmission and power directly from shore. The ASIT is located 3 kilometers due south of Edgartown Great Pond in 15 m of water, and extends approximately 22 m into the marine atmosphere. The ASIT was instrumented starting in the spring of 2003 in preparation for the CBLAST IOP. The instrumentation provided measurements of the wind speed and direction, air and sea temperature, humidity and salinity, wave height and direction, and currents at the offshore site. More importantly, the ASIT was outfitted with sensors that provide direct and remotely sensed measurements of the momentum, heat, and mass fluxes across the coupled boundary layers. The wide variety of sensors deployed to characterize the CBL is shown in Fig. 2. As shown in Fig. 2a, this included a fixed mast that held sonic anemometer/thermometer paired with infrared hygrometers at the lowest 3 levels and sensors capable of measuring static pressure at 2 of those levels. A profiling mast was deployed toward the end of the IOP to measure mean profiles to go with the turbulent fluxes through mid-October. The profile measurements from this setup will also be used to provide an in situ calibration of the fixed sensors on the rest of the ASIT. Additional measurements above the sea surface included instantaneous wave height estimates from laser and microwave altimeters; shortwave radiation, longwave radiation, and upwelling brightness temperature from radiometers; three more levels with sonic anemometers a rain gauge, and multiple levels with relative humidity/temperature sensors.

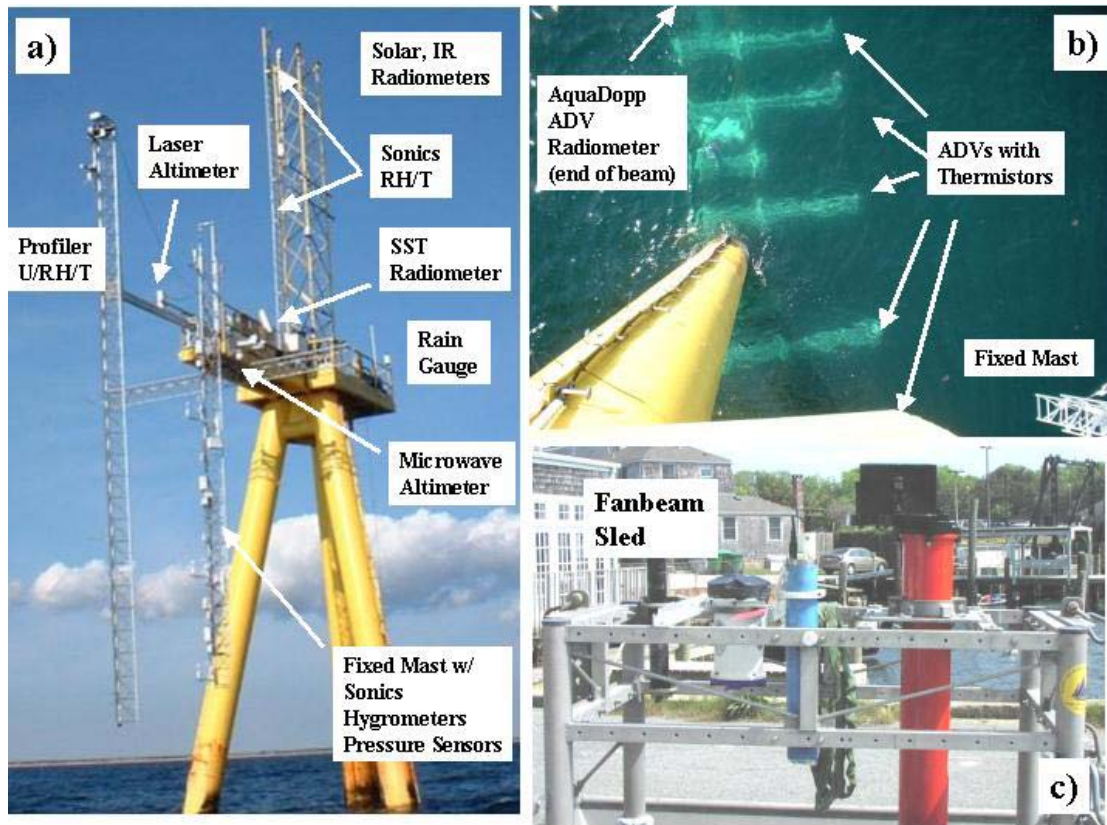


Figure 2. *A composite of some of the instruments deployed on the ASIT during the 2003 main experiment: a) The atmospheric components with masts supporting sensors to measure turbulent fluxes and their associated mean profiles, b) the near surface oceanic components (shown from above) with a horizontal beam deployed across the legs to support booms that held sensors to measure turbulent fluxes and associated mean profiles, and c) the fanbeam sled with instrumentation to measure the current shear and coherent structures in the water column.*

Some of the oceanic sensors deployed to measure the near subsurface velocity field are shown in Fig. 2b. These sensors were deployed from booms that extended outward from a horizontal beam mounted across the WSW facing legs. These sensors included 6 ADVs paired with thermistors to provide estimates of the momentum fluxes, heat fluxes, and directional wave spectra. Subsurface pressure sensors were also mounted to measure the wave field. A vertical array of temperature/salinity sensors was mounted at the end of the beam with a high resolution ADCP (AquaDopp). The purpose of these measurements is to monitor the mixed layer depth, determine the wind-driven flow in the mixed layer, and provide context information for the flux measurements being made by the ADV array.

A bottom lander “sled” (shown dockside in Fig. 2c) was deployed 40 m south of the ASIT. The sled contains a “fanbeam” ADCP, a conventional profiling ADCP, a T/C sensor, and a pressure sensor that uses burst-sampling (3 hr intervals) to characterize the surface wave field. These instruments operated from 1 June to the end of August, and are presently being refurbished for re-deployment through late October. The fanbeam ADCP detects the horizontal flow field at the surface with resolution of about 2 m and a total range of about 100 m. The purpose of these measurements is to detect horizontal convergences due to Langmuir circulation (LC) or other phenomena (e.g. internal waves).

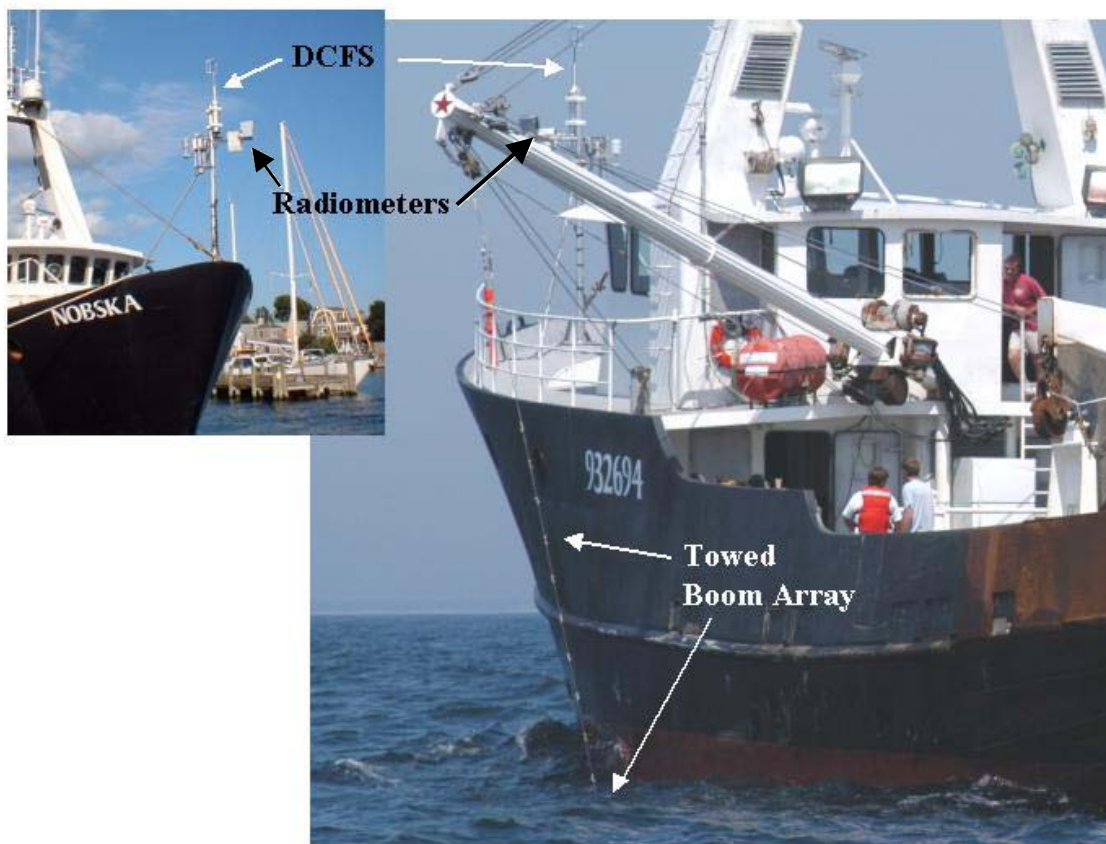


Figure 3. Some of the instrumentation deploy off the Nobska during the IOP. The bow mounted instrumentation included a sonic anemometer, an infrared hygrometers, and infrared radiometers. The boom array towed a string of temperature sensors (T-chain) between the surface and a depth of 20 m. The Nobska crew also deployed 5 surface drifters instrumented with T-chains during the IOP cruises. Results from these instruments are shown in Figs. 7 through 9.

The mooring component deployed the 5 heavy surface moorings shown in Fig. 1 in mid-July. These moorings supported temperature, salinity and velocity sensors with 2-m resolution in the vertical. Three of these heavy moorings support a full suite of IMET instrumentation for air-side measurements. The IMET buoys will provide heat, freshwater, momentum fluxes using bulk formula to investigate spatial variability of the fluxes that force/respond to ocean, provide realistic forcing fields to ocean modelers, verify atmospheric model surface meteorological and flux fields, and contrast the closer to shore ASIT and MVCO sites with offshore sites. An additional 10 light surface moorings were deployed at the start of the IOP. The light moorings supported temperature sensors with 2-m resolution to provide, in combination with the heavy moorings, a continuous 3-D picture of the oceanic temperature field to investigate the role of mesoscale variability in upper ocean dynamics and air-sea interactions.

Four survey cruises were conducted on the Nobska (see Fig. 3) over the course of the IOP. The surveys deployed and tracked 5 drifters each outfitted with a densely instrumented subsurface temperature/pressure array (0.5 m resolution) and two levels of salinity measurements. The surveys also deployed a boom array off the side of the ship to tow a similar T/S/P array through targeted surface features and routinely made CTD casts. The ship supported upward and downward looking KT-19 radiometers provided by Jessup/Zappa. The radiometers provided estimates of the sky and

surface brightness temperatures that will be converted to skin temperature estimates. WHOI also deployed a direct covariance flux system on the Nobska along with shortwave and longwave radiometers to make continuous measurements of the momentum, heat, mass, and radiative fluxes during the oceanic surveys. As with the IMET buoys, these measurements will be combined to compute the total heat flux entering the ocean during the surveys.

The WHOI efforts were closely coordinated with the aircraft efforts. For example, the boom array was routinely towed through features identified during the IR aircraft flights. Additionally, the DCFS fluxes, measured at 8-m, will complement the 30-m flux estimates measured from the CIRPAS Pelican. Analogous to the flux estimates, the radiometer measurements from the Nobska will complement the IR aircraft measurements and provide a strong link between these two platforms.

Finally, WHOI PIs collaborated with Qing Wang of the Naval Postgraduate School to deploy measurements at the Nantucket island field site. Dr. Wang and her colleagues deployed mean and turbulence sensors on a meteorological mast near the shoreline, launched rawinsondes, and operated a SODAR to profile the atmospheric boundary layer. WHOI supported these efforts by providing measurements of solar radiation, infrared radiation, and atmospheric pressure, as well as redundant measurement of temperature, humidity, and wind speed.

RESULTS

The combination of the ASIT, MVCO, the Nantucket field site, the 5 heavy moorings (3 with full meteorological packages), and 9 of the 10 light moorings (i.e., one was lost) shown in Fig. 1 will provide the CBLAST PIs with time series from 7 spatially separated locations with meteorological data and 18 locations with oceanographic data. The point measurements will be combined with the spatial surveys from the two aircraft and the Nobska to investigate the processes that the exchange of momentum, heat and mass across and within the coupled boundary layers. Analysis of this data has begun, as has interaction with the CBLAST-LOW oceanic and atmospheric modelers about their ability to replicate the observations in their hindcasts.

An example of the high quality atmospheric flux estimates measured on the ASIT is shown in Fig. 4. The upper panel shows time series of the along- and cross-wind stress components measured by separate flux packages deployed at 6 and 8. The lower panel shows time series of the latent and sensible heat flux. The agreement between the two levels is remarkable. The non-zero values of the cross-wind stress components indicate a difference between the stress and wind vectors. We plan to investigate whether the difference is related to misaligned swell and wind vectors in light wind conditions. This particular time period experiences sensible heat fluxes indicative of both stable and unstable conditions, which will allow investigations of varying stratification on the exchange processes. Interestingly, the latent heat fluxes at both levels show evidence for a downward flux of moisture. We plan to investigate the role of the downward flux in the formation of fog at low winds.

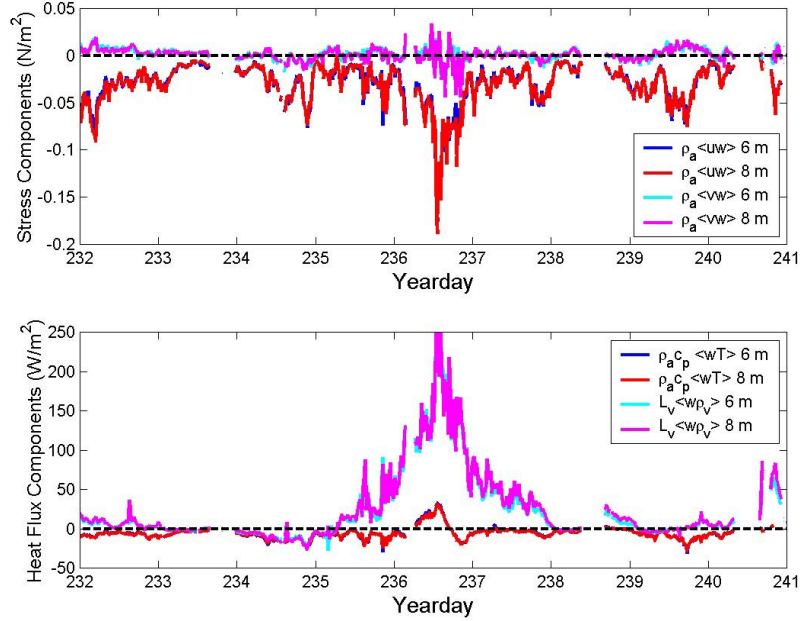


Figure 4. Time series of atmospheric flux measurements made from the ASIT. The top panel shows the along- and cross-wind components of the stress vector measured at two elevations, while the bottom panel shows the sensible and latent heat fluxes from those levels. Yearday 232 is August 20th.

The subsurface boom was deployed on the ASIT and instrumented during the second half of the IOP. Preliminary results from the first week of this deployment are shown in Fig. 5. The subsurface stresses shown in this figure were derived from the two ADVs at the end of the subsurface boom. To obtain these results, a technique that relies on differencing velocities obtained from horizontally separated ADVs is used to remove the irrotational motion of the surface waves. **To our knowledge, this is the first comparison of coincident direct covariance Reynolds stresses measured on both sides of the interface.** The agreement between these estimates is good and we expect to improve the quality of the flux estimates and resolve the discrepancies in Fig. 5 as we implement continue the analysis. The agreement between these fluxes is very encouraging and we look forward to analysis of the complete data set that we collect through the fall.

Preliminary results from the Fanbeam ADCP data are shown in Fig. 6. Data from 19 August are highlighted to provide an example of LC variability in low to moderate winds. This day was chosen due to the wide range of wind speeds (0.5 – 8.0 m/s) and relatively steady wind directions (+/- 20 deg during analysis segments). Four analysis segments were chosen (Fig. 6a), representing wind speeds of approximately 0.5, 2.5, 5 and 8 m/s, respectively. For each segment, 30 min of fanbeam data were processed to highlight anomalies relative to range and time mean values. The velocity anomaly is plotted as a time-range map for an ADCP beam pointed approximately cross-wind. In the presence of Langmuir circulation, the time-range map shows alternating zones of convergence and divergence that appear to “propagate” as a result of advection by lower frequency currents. During segment 1, there was no evidence of organized patterns associated with LC, although we note that small and/or weak circulation could have been below our detection threshold. Segment 2 showed weak evidence of convergence zones that will require further analysis. Segments 3 and 4 showed clear evidence of LC with velocities of 4-6 cm/s and “windrow” spacing of 25-50 m (Fig. 6b).

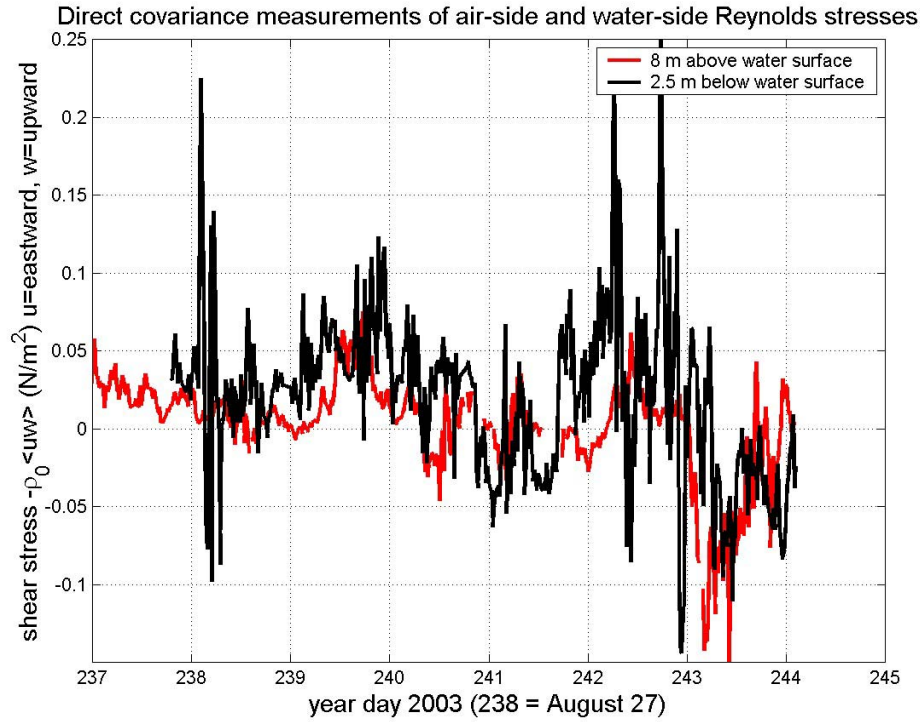


Figure 5. Direct covariance measurements of the Reynolds stresses as measured above and below the air-sea interface. Twenty minute averages are used in these calculations.

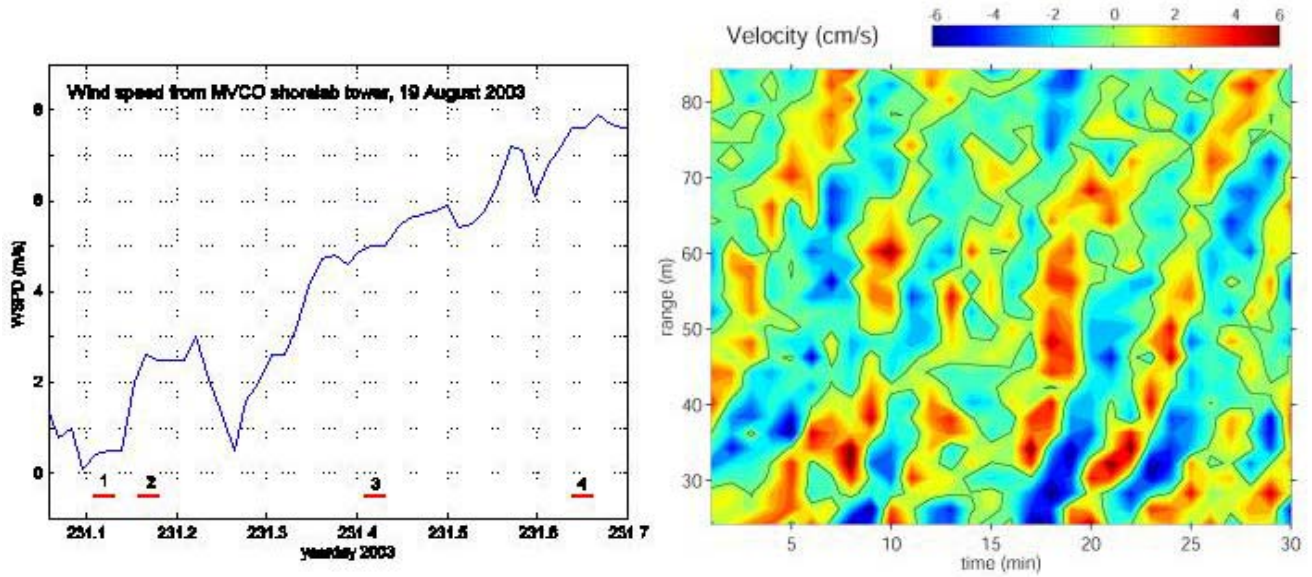


Figure 6. a) Wind speed ranging from 0-8 m/s as measured at the MVCO tower for 19 August 2003. Red bars denote analysis segments. b) Surface horizontal velocity vs. time and range during segment 3. Alternating positive and negative bands indicate LC; slant is due to mean advection of cells relative to the instrument.

The Nobska conducted 4 cruises during the IOP in a wide variety of conditions. Some of the towed and drifting array results have been processed and combined with the DCFS results. An example of

the type of processes studies we will investigate is shown in Fig. 7 where DCFS fluxes are combined with the boom tow-chain measurements. The figure shows the cruise track overlaid on the SST field from the same day, and other figure highlights the spatial variations seen on this track. The surface fluxes are clearly responding to the spatial variability in the SST field. A striking feature that is of particular interest is the dramatic change seen in both latent and sensible heat fluxes (nearly 200 W/m^2 total) as the vessel moved across the narrow oceanic frontal zone. Snapshots like these over the course of the day shows diurnal warming over the entire regions. We hypothesize that the rate at which sub-regions warm and the corresponding response of the mixed layer will depend on the magnitude of the surface fluxes “locked” over these sub-regions. We expect to rely on the higher resolution IR aircraft SST fields in this analysis as well as low-resolution AVHRR.

Trajectories derived from the ROM model forecasts and the GPS drifters deployed from the Nobska are shown in Fig. 8. This figure provides an example of how the data sets could be used to evaluate the mesoscale models run as part of CBLAST. Direct comparisons between the model runs and measurements will require collaboration between the CBLAST PIs to remove the differences between, e.g., the depth-averaged trajectories provided by the measurements and the fluid parcel trajectories provided by the model. In fact, the objective of the drifter experiments is to look more at the varying temperature structure beneath the surface floats. Therefore, we expect our investigations to initially focus on processes studies and model evaluations using the temperature/salinity measurements taken from the mooring array, drifters (see Fig. 9) and the towed T-chain.

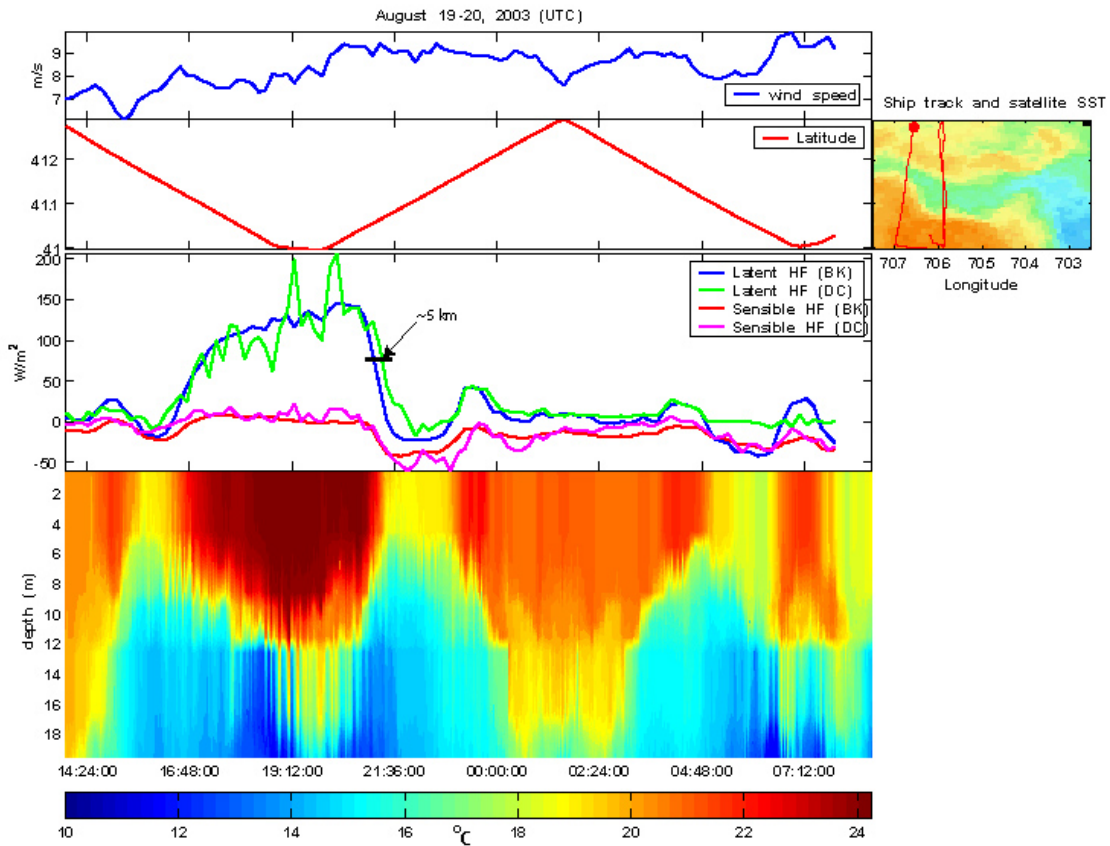


Figure 7. Ship survey results from the towed boom array and DCFS on the Nobska showing the wind speed, ship position, flux estimates, and time-depth cross section of the temperature field. The surface feature corresponding to these transects are shown in the inset.

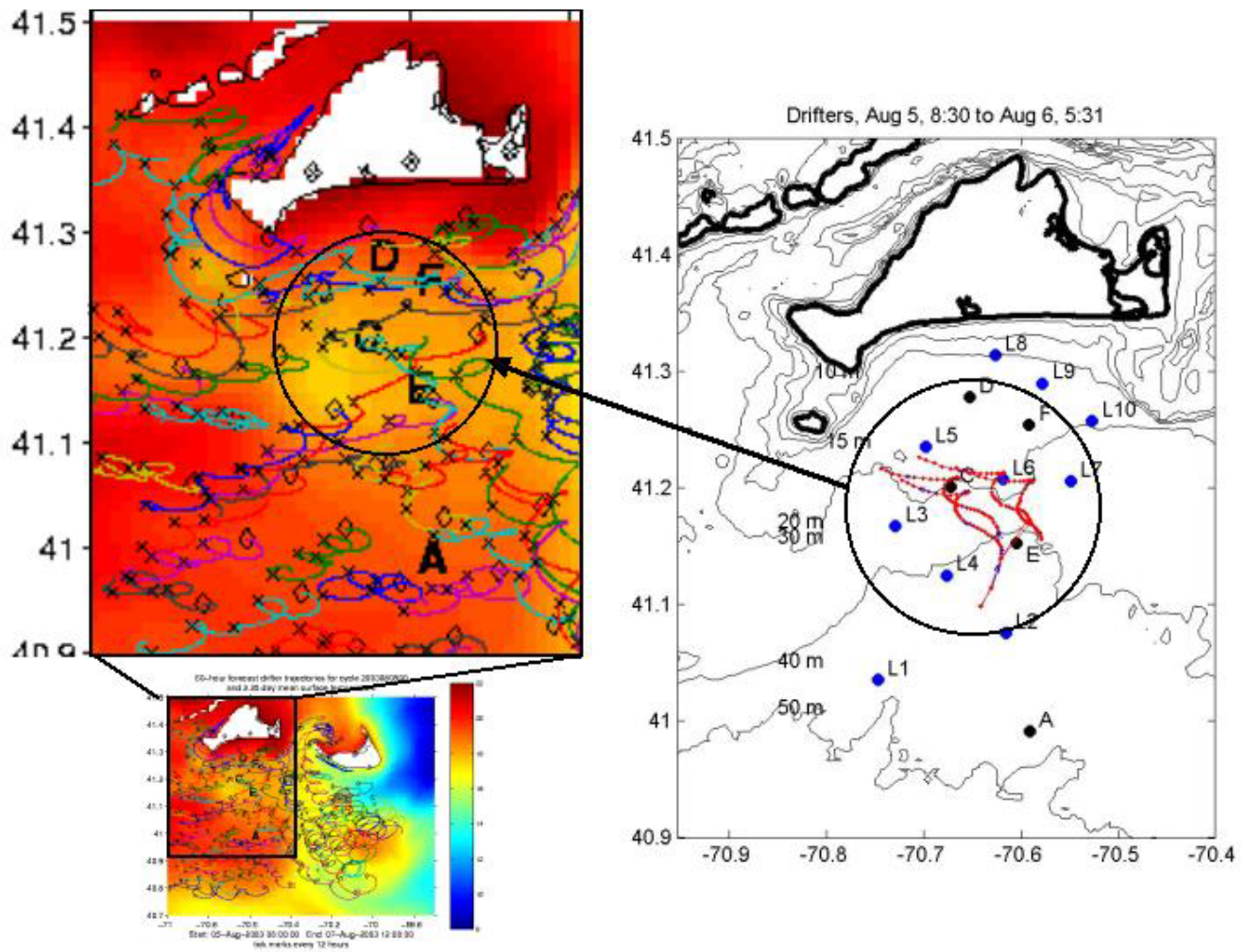


Figure 8. An example of the type of data that will be used for our process studies and model evaluations. The plots on the left are taken from the 72-hour ROMS forecast runs for August 5-7, 2003. The lines in this plot represent near surface trajectories while the colors represent the near surface temperature averaged over the run. The plot on the right is derived from the drifter deployments on the Nobska August 5-6, 2003. Note that the model output represents near surface trajectories and that the measurements included a temperature chain beneath surface floats.

IMPACT/APPLICATIONS

The 2003 IOP component of the CBLAST field program was successfully completed in August. Data quality and return have been excellent, and a wide variety of conditions were sampled, including low-to-moderate wind conditions and the passage of strong atmospheric and oceanic fronts through the study region. The ASIT and the fifteen moorings that were deployed provide a complete time series of the passage of oceanic fronts and other processes with a spatial resolution on the order of 4 km, and the ship based measurements complement this data by providing a spatial resolution of about 8 m. In conjunction with aircraft-based measurements and satellite data, the *in situ* measurements collected during the 2003 IOP constitute an unprecedented record of the evolution of the coupled air-sea boundary layers. These measurements will facilitate a more complete understanding of the relative

roles of local air-sea interaction and other processes (e.g. ocean fronts and advection) in influencing the evolution of the coupled air-sea boundary layer in low-to-moderate winds. Through ongoing collaboration with numerical modeling groups, we anticipate that this data and improved understanding of air-sea interaction will contribute directly to improving the skill of marine forecasts.

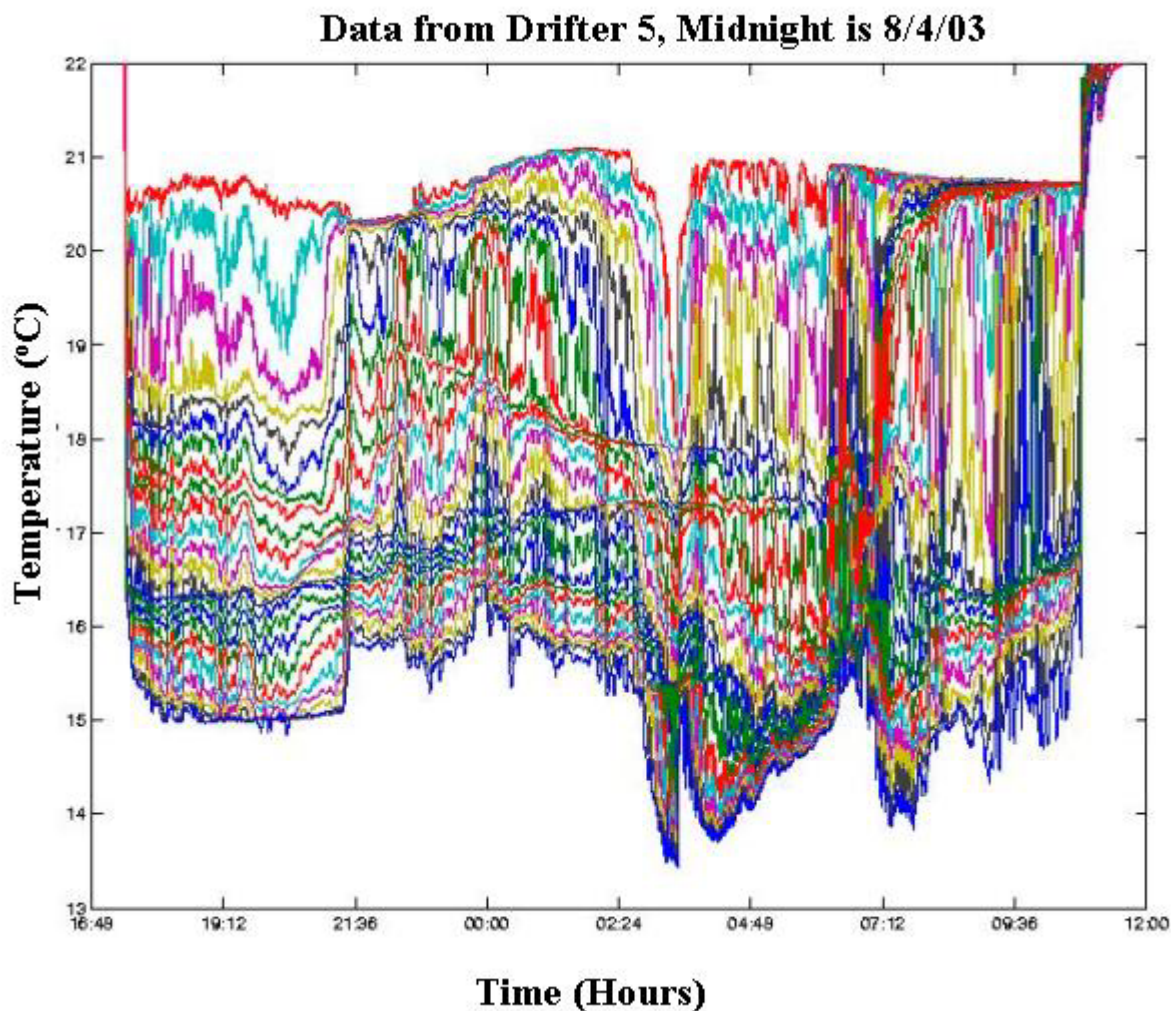


Figure 9. Temperature measurement from the T-chain deployed beneath the surface drifters. The upper trace (red line) is from approximately 2.2 m depth. The subsequent lines are at 0.5 m resolution down to the lower trace taken at a depth of approximately 14 m. The measurements collapse during launch and recovery.

TRANSITIONS

In addition to several ongoing ONR projects, the ASIT is being used by investigators funded by the NSF and NASA to conduct their research. The ASIT has become a component of the MVCO.

RELATED PROJECTS

John Trowbridge used an NSF SGER proposal to deploy sensors east and west of the ASIT to measure the pressure, temperature, and salinity gradient along the 15 m isobath. These measurements will be

used to continue our investigations of the cross shelf momentum and heat budgets in the CBLAST region. Melanie Fewings, a graduate student in the joint MIT-WHOI educational program, is funded under a separate ONR proposal to work on CBLAST. Lt. Robert Crofoot, a Navy funded graduate student in the joint program, is currently working on the CBLAST data. Additionally, since the fall of 2002, the ASIT and some of the CBLAST instrumentation and analysis has been used by several ongoing projects. This includes the ONR sponsored Surface Process and Acoustic Communications Experiment (SPACE), an NSF sponsored Bio-complexity project, and a NASA sponsored Ocean Color program.

This work is closely related to our studies of horizontal variability and predictability that was supported with one of the Secretary of the Navy/Chief of Naval Operations Chairs. That work has focused on the impact of environmental variability on mine countermeasures activities in the shallow water. We have deployed instrumentation to collect data in exercises both in the Gulf of Mexico and off Camp Pendleton. CBLAST-LOW has benefited directly from the development of light surface moorings, instrumentation, and data telemetry methods used in those exercises. In return, CBLAST-LOW, with its explicit sampling of the horizontal as well as vertical and temporal dimensions, will be of great help in assessing how well a single surface mooring can provide adequate information about oceanographic and meteorological variability in a specific region.

PUBLICATIONS

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A CBLAST-LOW overview paper is in preparation.